Field Measurements of the Influence of Bubbles on the Inherent Optical Properties of the Upper Ocean: Renewal.

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LONG-TERM GOALS

The long term goals of this project are to better understand the influence of air-sea interaction processes on hyperspectral remote-sensing of the ocean's surface.

OBJECTIVES

This research program is concerned with understanding the role of bubbles injected by breaking waves in modifying the inherent optical properties (IOPs) of the upper ocean. Surface-layer oceanographic phenomena such as turbulent mixing and Langmuir cells are also addressed in the investigation as they are known to play a large role in determining the depth to which bubble clouds penetrate, the bubble residence times, and the bubble size distributions. The data collected during this program is providing the necessary information for the development of physical models of the evolution of bubbles in the surface wave layer based on wind and wave forcing. Models of remote sensing reflectance are being extended from these synoptically forced bubble models to understand the role of bubbles in modifying the optical properties of the upper ocean. A byproduct of this research will be models to correct for bubble mediated effects in measured hyperspectral light fields using wind and wave information. The program also presents the opportunity to develop techniques for inverting remotely-sensed hyperspectral imagery for in-situ bubble concentrations.

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APPROACH

As part of the Hyperspectral Coupled Ocean Dynamics Experiment (HYCODE), a field sampling program was designed for measurements of bubbles and IOPs over a range of sea states. The variability of the bubble field that results from wave breaking necessitates that the bubble and optical field be sampled with sufficient temporal and spatial resolution. Acoustic techniques that have been refined over the last decade (Terrill & Melville, 2000) are used for measuring the bubbles in conjunction with optical measurements to directly measure the bubble field and the resulting optical scattering. A Monte-Carlo Radiative transfer model has also been developed and applied to the problem of computing remote sensing reflectance from IOPs that are heterogeneous in space. Results from the modeling are being coupled with the physical measurements to provide insight on how to extend the results to satellite-based remote sensing assets which have large pixel footprints that would integrate over many different spatial patches of bubbles.

WORK COMPLETED

While the first few years of this program have been focused on developing measurement capabilities, data collection, and data analysis, our efforts are now focused on advanced analysis, modeling, and publication efforts. Details related to the accomplishments associated with the field intensive effort in the earlier years of the program have been summarized in earlier reviews. These efforts have included field studies conducted at the LEO-15 site off the coast of Tuckerton, New Jersey and at site offshore the windward coast of Oahu, Hawaii using the Research Platform FLIP. The contrast in the optical complexity of the waters has provided an opportunity to study bubble related phenomena in both case 1 and case 2 waters. New Jersey's relatively benign sea conditions and turbid water prompted us to examine other sites which would allow us to examine the influence of bubbles on marine light fields in clear waters. However, despite the turbid waters experienced in New Jersey, we were able to obtain a wealth of information on the impact of dense of bubble clouds on near surface water IOPs. This data was obtained using time series obtained from an air-sea interaction buoy that was deployed with acoustic and optical sensors as well the use of a small boat that allowed us to measure the spatial scales of the bubble populations.

The opportunity to use FLIP offshore Hawaii was provided by ONR's support of the Rough Evaporation Duct (RED) Experiment. RED had complementary objectives to HYCODE in its need to measure surface waves and aerosol populations to better understand EM and EO propagation. Time series of IOPs and bubbles were again obtained by our group using optical and acoustic instruments. After our successes in New Jersey to measure bubble influences on IOPs, we expanded our measurement effort to also obtain a time series of the remote sensing reflectance using a suite of hyperspectral radiometers. These radiometers were deployed from the face boom of FLIP with consideration to prevent hull shading from influencing the measured water leaving radiancs. The multi-week time series provided us an opportunity to examine the variability of the remote sensing reflectance on short (O(1) second) time scales corresponding to breaking events and longer time scales that corresponded with wind events. Analysis efforts with the radiometer data have focused on understanding trends in the measured reflectances. Central to this effort is the goal to separate the sky reflectance from the water leaving radiances which presumably would reflect the signature of bubbles during the higher sea states. While indeed the measured Lw/Ed (both sensors were above water) does scale with the sea state, removing sky reflection and sun glitter which is also sea state dependent has proved difficult. Since the effects of sun glint can be minimized by choosing appropriate sun angles and removing saturated spectra, the sky reflection problem has proved difficult since the sky radiance

distribution was not measured. The atmospheric correction algorithms that exist do have a wind speed dependence of the surface roughness, they have been designed primarily for satellite-based, kilometer sized pixels. For the few m^2 spot size that we are sampling, shortcomings in these algorithms becomes readily apparent. A known example of this is the ability to image ocean swell by a hyperspectral sensor such as PHILLs or AVIRIS, even after 'atmospheric corrections' have been applied which should account for the wind speed / surface roughness dependence. This is due in part to the statistical description attributed to the surface roughness which does not account for small scale variability. In the case of the ocean swell, the capillary waves responsible for reflecting the light are modulated by the longer period swell. Internal waves can also modulate the capillary waves by similar processes which strain the sea surface. Below is an image obtained by the FERI operated PHILLS sensor which was flown off San Diego as part of a HYCODE-related effort. The image clearly shows a packet of high frequency internal waves with O(200)m wavelengths. No vessel wake or swell was present in the region to generate surface waves, but the area is known for internal wave activity.

Our work with a Monte-Carlo radiative transfer model has continued to examine the remote-sensing reflectance that results from idealized bubble clouds defined by our field measurements. The model allows us to examine these influences as a function of both optical wavelength, chlorophyll concentration, or other background optical constituent. Papers our currently being drafted which describe the model and results from the modeling efforts. A near-term goal is to use our understanding of the spatial statistics of bubble clouds and extrapolate the results to understand the influence of bubbles on remote sensed pixels of O(1) km. This will involve a method of superposition which will couple our model results of individual bubble clouds with the statistics breaking waves.

PRELIMINARY RESULTS

- Optical scatter from bubbles is transient in space and time. Optical scatter can be O(10) m^{-1} or more. The relevant space scales of the collections of bubbles that result from wave breaking are O(1)m over the range of wind speeds studied (maximum of ~10ms^{-1}).
- Optical scattering resulting from active breaking waves is relatively spectrally flat, with the dominant bubble sizes contributing to optical scattering being 50-100 microns in size. Enhancement to the RSR in the blue-green will depend on the relative concentrations of the other water-borne optical constituents present. The phase functions of bubbles are inherently different than other optical constituents found in the ocean, with scatter in the forward direction much more significant.
- Results from the Monte Carlo modeling effort indicate that even small bubble clouds produce water leaving-radiances that are significant even in the near infrared spectral region and will impact algorithms which assume zero water leaving radiances at this wavelength
- Monte-Carlo modeling efforts indicate that the horizontal and vertical gradients in the bubble field result in a heterogeneous light field which can not be reproduced by slab models which assume homogeneous horizontal distributions of IOPS.
- To completely remove sky reflection from above water measured light fields over small footprints will require a measurement of the 2-D wavenumber spectrum of the capillary-gravity waves which are responsible for reflecting the light (amplitude and phase), a measured distribution of the sky radiance field, and a complete model of photon propagation from the sun to the receiver. Without this information, extracting subtle signatures such as dilute bubble populations which are transient in time will prove difficult. We anticipate that at higher wind speeds, the ability to resolve the bubbles would be much easier. Unfortunately, the winds only briefly exceeded 10 ms^{-1} at the Hawaii study site – uncharacteristic for the season.

IMPACT/APPLICATIONS

The discrimination between Case 1 and Case 2 waters loses its meaning if we recognize that the scattering properties of near-surface waters can be largely determined by gas bubbles whose concentration and size distribution (i.e. major determinants of optical scattering) vary greatly in time and space as a function of wind and wave conditions. Consequently, one can argue that even Case 1 waters, do not exist in the top few meters of the ocean which are the most important for remote sensing of ocean color. Part of the error in the data products generated by the existing ocean color algorithms can certainly be attributed to variable concentration of gas bubbles submerged in the near surface layers. As an example, the existing parameterizations of backscattering coefficient in the semi-analytical algorithms for inverting reflectance measurements will most likely be biased by the presence of the sea state dependent bubble backscatter. In addition, submerged bubbles can influence the validation of the atmospheric correction, which is based on the comparison of in situ and satellite-derived water-leaving radiances. The quantification of these errors at the present time is, however, impossible because no simultaneous data exist that characterize optical properties and bubble populations in the water. It is anticipated that results of this research will provide an indication of these errors. Furthermore, we expect that the results of the research will provide opportunities in the future for remotely sensing air-sea interaction processes using hyperspectral optical techniques.

TRANSITIONS

Discussions with several DOD labs and contractors have taken place as bubbles are increasingly being recognized as an important optical constituent in VSW scenarios. Insight gained on our analysis efforts relating surface roughness to remote sensing reflectance should also be of interest to the applied community.

PUBLICATIONS IN DIRECT RESPONSE TO THIS PROGRAM

Piskozub, Jacek; Stramski, Dariusz; Terrill, Eric; Melville, W. Kendall - 3-D RADIATIVE TRANSFER MODELING OF THE EFFECT OF BUBBLE CLOUDS ON REMOTE-SENSING REFLECTANCE. Ocean Optics XVI. 2002

Terrill, Eric; Melville, Ken; Stramski, Dariusz – Influence of bubbles on marine optical properties. Ocean Optics XVI. 2002

Piskozub, J, Terrill, E.J., Error estimates in sea water absorption measurements from multiple scattering and forward scattering. Applied Optics 40pp. IN PREP (2002).

Terrill, E.J., W.K. Melville, and Stramski, D. 2001 Bubble Entrainment by Breaking Waves and their Influence on Optical Scattering in the Upper Ocean. J. Geophys. Research. 16,815 - 16,823.

Terrill, E.J., W.K. Melville, and Stramski, D. 1998. Bubble Entrainment by Breaking waves and their Effects on the Inherent Optical Properties of the Upper Ocean. SPIE Ocean Optics OOXIV, Kona, HI. November 1998.

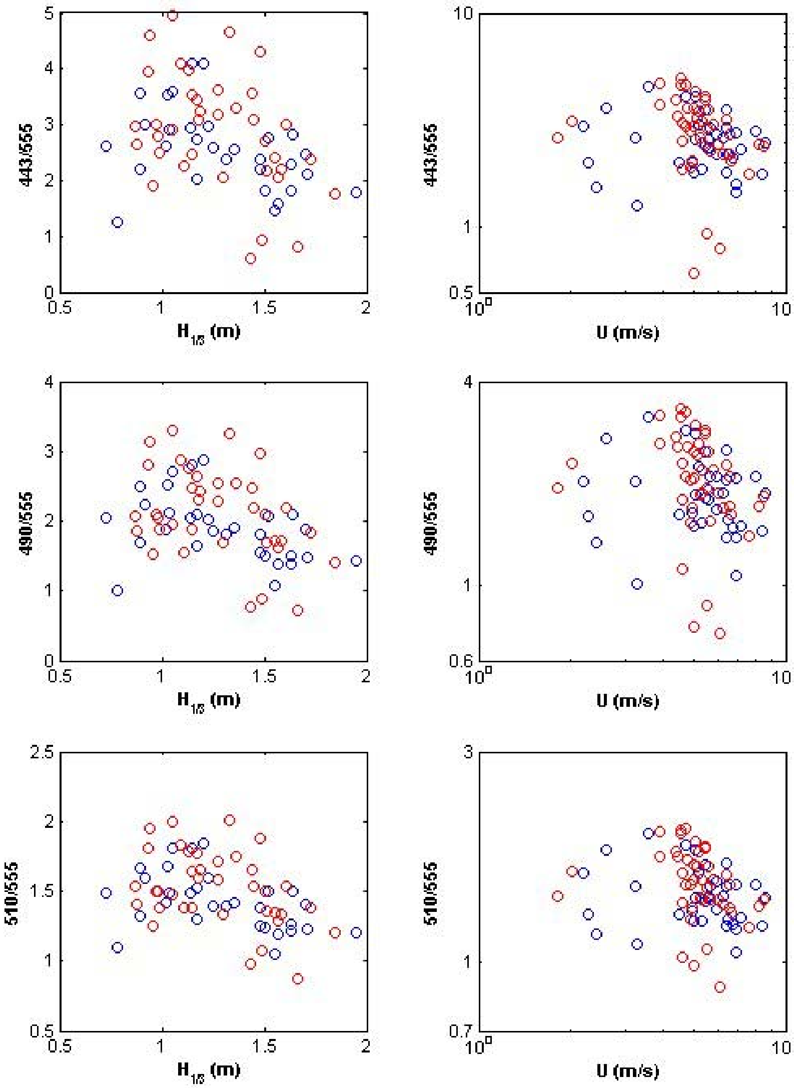

Figure 1. Band ratios for common chlorophyll retrieval algorithms using measured remote sensing reflectances off the coast of Oahu during September 2001. Data was obtained using hyperspectral radiometers deployed on a boom attached to FLIP. The hourly averaged data is plotted against the significant wave height and wind speed. All bad spectra have been removed from the data and only data with the same solar angle are shown. With an assumption that the IOPs have remained relatively constant over the time period of the measurement campaign (a good assumption considering our location), we attribute the scatter in the data as a result of changes in sea state. A rational method of extracting sea surface sky reflection that varies with sea state to allow us to resolve the influences of the bubbles on water leaving radiances has proven difficult.

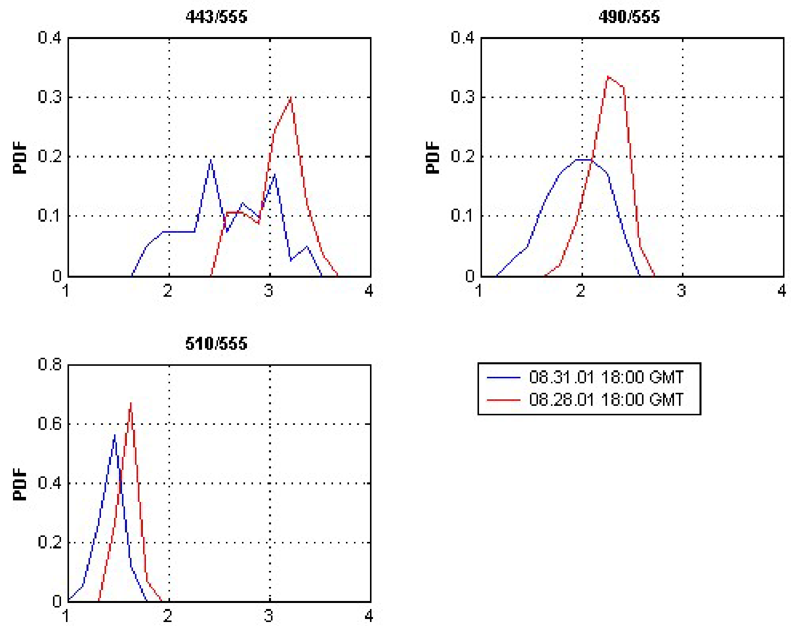

Figure 2. The PDF of the same band ratios using successive hyperspectral scans obtained over 1 hour during calm conditions (red line) and rough conditions (blue line). The statistics demonstrate the influence of the sea state when measuring light fields over small pixel sizes. In this case, the spot size is a few m^2.

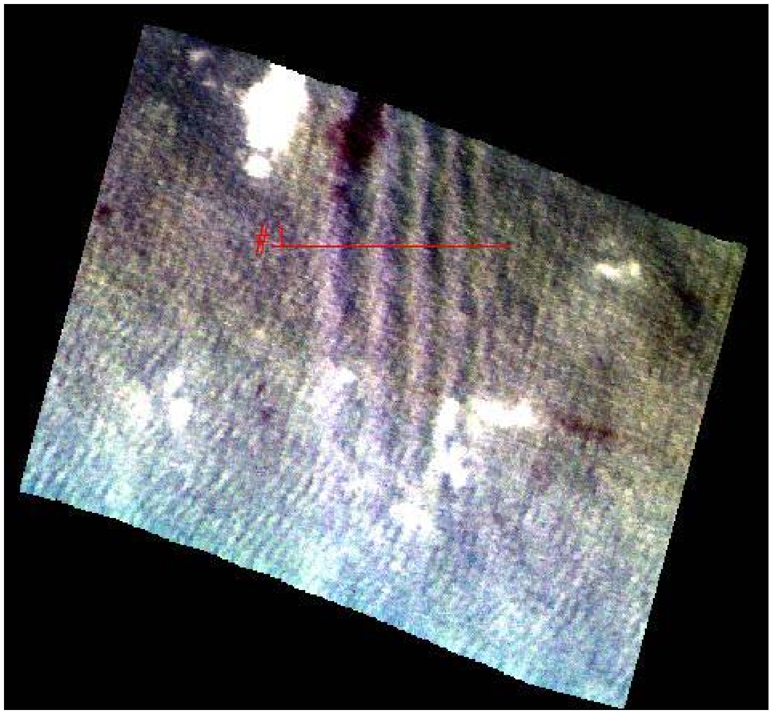

Figure 3. An enhanced image of PHILLS hyperspectral data obtained off the coast of San Diego near Point Loma. The image shows both surface waves and what appears to be an internal wave. The internal wave has wavelengths of O(200)m (the red line is transect over the wave feature). The image graphically illustrates how capillary waves modulated by surface or internal waves will result in differences in measured light field. Analysis efforts are still ongoing to better relate the internal wave packet to the measurements.

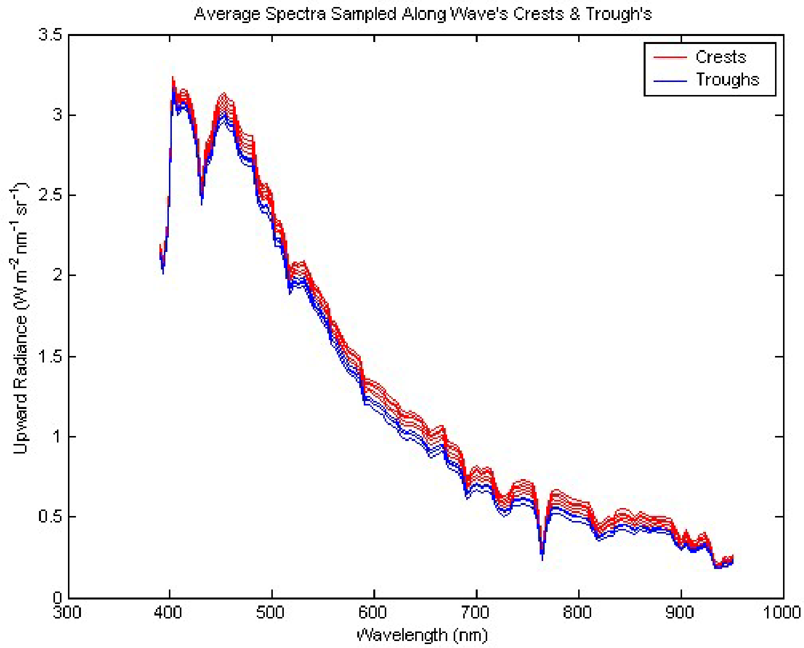

Figure 4. Light spectra averaged over all crests (red) and troughs (blue) across the internal wave packet image shown above. While there appears to be little spectral enhancement across the measured bands, the light field at the crests appear to have an overall upward shift, perhaps as a result of increased surface roughness in these regions. A profile of IOPs in the region indicated little optical stratification which may explain why there is little spectral response across the wave features.